

Optimization of feed distribution to sea caged fish with an emphasis on Atlantic salmon (*Salmo salar* L.)

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A thesis submitted as a requirement for the Masters Degree of Applied Science in Aquaculture, University of Tasmania, School of Aquaculture, Launceston, December 2000.

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A handwritten signature in black ink, appearing to read 'Peter John Blyth', with a long horizontal flourish extending to the right.

Peter John Blyth
15th December 2000

Contents

i. Abstract	5
ii. Acknowledgments	7
iii. List of Tables	8
iv. List of Figures	9
v. List of Publications	11
vi. General Introduction	12
1. The “Adaptive” Feeding system: preliminary studies	14
1.1. Description of the “Adaptive” feeding system	14
1.1.1. Introduction	14
1.1.2. System components	15
1.1.3. Calibration of the system in a commercial sea cages	20
1.2. Detection of feeding rhythms in sea-caged Atlantic salmon using new feeder technology	19
1.2.1. Introduction	19
1.2.2. Methods and Materials	20
1.2.3. Results and Discussion	23
1.2.4. Conclusions	25
1.3. Do adult Atlantic salmon feed at night in sea cages?	27
1.3.1. Introduction	27
1.3.2. Methods and Materials	27
1.3.3. Results and Discussion	27
2. Diurnal and seasonal variation in feeding patterns of Atlantic salmon in sea cages	39
2.1. Introduction	39
2.2. Materials and Methods	40
2.3. Results	41
2.4. Discussion	41
3. Can compensatory growth improve the profitability of Atlantic salmon aquaculture?	46
3.1. Introduction	46
3.2. Materials and methods	46
3.3. Results	48
3.4. Discussion	49
4. Application of the “adaptive” feeding technology in the industry: feeding patterns and production results from several cultured species	54
4.1. Feeding strategies and temporal feeding patterns of several cultured fish from Australia and New Zealand	54
4.1.1. Introduction	54
4.1.2. Feed distribution technology	55
4.1.3. Feeding Strategies	55
4.1.4. Comparative feeding patterns	56
4.1.5. Application to Japanese species	59
4.1.6. Conclusion	59
4.2. Feed optimization in finfish culture using an integrated “feedback” system with special reference to yellow tail, <i>Seriola quinqueradiata</i>	68
4.2.1. Introduction	68
4.2.2. Preliminary feeding trials with Yellow tail <i>Seriola quinqueradiata</i>	69
4.2.3. Discussion	71

vii.	General Discussion	75
viii.	References	79

i. Abstract

The aquaculturist is faced with a number of difficulties when feeding fish. Apart from the human time component involved in feeding a large number of fish to appetite, it is important to feed an appropriate quantity at a suitable frequency to ensure that no food is wasted and fish are satiated. Fish display preferential feeding patterns that relate to endogenous rhythms and changing biological and environmental factors. This study describes a new technology called the "Adaptive" Feeding System designed to automatically feed fish by regulating feed input based on the levels of waste food detected beneath a feeding zone. A series of trials with the system are also discussed.

The system consisted of a surface mounted microprocessor linked to an underwater sensing device capable of resolving a single feed pellet. An internal algorithm controlled the operation of the system. Feeding data was stored by the microprocessor and down loaded via a data-logger to an IBM-compatible computer for analysis with specific software.

Atlantic salmon, *Salmo salar*, in sea-cages exhibit feeding patterns which vary both diurnally and seasonally. Hitherto, there are no data reporting feed rate and its variation through a complete annual cycle. Here we present data from Scotland showing diurnal and inter-seasonal variation in feeding patterns and feeding rates of Atlantic salmon fed daily to satiation from shortly after transfer to seawater until harvest about 11 months later. A major feeding peak regularly occurred soon after dawn, and feeding rates remained high for approximately one hour. Over the remainder of the day the fish fed at a lower, but steady rate. Relative feed intake varied over the trial, being initially high in summer followed by a sharp decline in autumn, and then further declining until fish reached harvest size at the beginning of the following summer. Further investigations of the relationship between variation in circannual feeding patterns and environmental parameters should now be carried out to improve the understanding of the mechanism behind these patterns.

Tasmanian Atlantic salmon (2-3kg) fed daily to satiation for four months over winter displayed a diurnal pattern of feed intake. The first peak of intake commenced just after dawn for 2-3 hours during which up to 60% of the total daily feed intake occurred. Some feeding occurred during the middle of the day but this was eclipsed by a significant feeding bout approximately 30 minutes before total darkness in the evening. This typical diel pattern often disintegrated due to changes in environmental factors but more significantly due to suspected disturbance by human activity or the presence of predators. Surface activity of the salmon, in response to feed input, and to a lesser extent swimming speed of the fish, were found to be reasonable indicators of feed intake. A better indicator of feed intake was measured by monitoring small quantities of waste feed sensed by the adaptive feeding systems' sensor.

A further study, investigating the effect of restricted feeding periods followed by re-feeding to satiation was carried out on Atlantic salmon (approx. 1.3kg) during winter/spring on growth. Four treatments included those fed daily to satiation (A), those fed for 5 days then starved for 2(B), those fed for 10 days then starved for 4(C) and those fed for 7 days then starved for 7(D). Every 28 days growth was measured by weight. Group A showed significantly higher growth ($p < 0.05$) in weight than the other treatments over 4 months. Groups B and C showed similar growth and Group D

displayed the poorest growth. The ability of periodically starved salmon to catch up in size to continually fed salmon was not apparent from this experiment. The results differ from other studies that have shown finfish can compensate totally for lost growth.

The application of the “Adaptive” feeding technology to other fish species, including Atlantic salmon (*Salmo salar*) in Scotland, Chinook salmon (*Oncorhynchus tshawytscha*) in New Zealand, barramundi (*Lates calcarifer*) in Northern Australia and yellow-tail (*Seriola quinqueradiata*) in Japan, was undertaken. Improvements in production performance due to satiation feeding and the use of the “feedback” system were noted which included a reduction in FCR 5-20% and a 10-40% reduction in production time for similar harvest weights.

ii. Acknowledgments

The author would like to individuals, companies and institutes that assisted this project through their advice, finance and use of equipment.

These organizations are Aquasmart Pty. Ltd., School of Aquaculture (University of Tasmania), Gibson's Ltd., SALTAS Pty. Ltd., Huon Aquaculture Company Pty. Ltd., Marine Harvest McConnell (MHM), Hisayoshi Fisheries Association, Moore-Clark Japan (Nutreco), AusIndustry formerly the Department of Industry Technology and Commerce (DITAC) and the Australian Fisheries Research and Development Corporation (FDRC).

Thanks goes to my supervisor John Purser, Peter Bender and the staff of Huon Aquaculture Co., Craig Foster, Kenny Mc Glennon of MHM as well as Sunil Kadri, Sveinn Valdimarrson, Vimal Parashar, Neil Metcalfe, Felicity Huntingford and John Thorpe all for their practical input. John Russell deserves a special mention for his design and innovation in development of the feeding system used in the study. I would also like thank my family for their patience and support and of course the fish.

iii. List of Tables

Table 1.1. Showing the treatment and system parameters

Table 2.1. Diet type and the content of oil and protein as a percentage of the total composition of the feed used throughout the annual cycle.

Table 2.2. Results of a repeated measures ANOVA showing the effect of time of year (month) and part of day (1st hour of the day against the remainder of the day) on the average feed intake (% Body-weight per hour) of sea-caged reared Atlantic salmon.

Table 2.3. Mean weight gain (g) and feed conversion ratio (FCR) of Atlantic salmon reared in sea cages throughout an annual cycle. FCR data are represented as mean \pm S.E. (n=3). Mean weight gain from one replicate cage is represented.

Table 3.1. Mean weight(kg) of salmon over 120 days for each regime. Each mean is calculated from the combined values of the three replicate cages. Different letters beside mean values within the same column indicate significant differences ($p < 0.05$).

Table 3.2. The coefficient of variation (%) of the mean weight for each regime over the experiment.

Table 3.3. Summary of the relative cost of production (A\$ per kg), from 6.6.90 to date of harvest using total harvested HOGG weight (kg).

Table 3.4. Estimated costs of production per kilogram HOGG for the average Tasmanian salmon farm.

Table 3.5. The cost difference (\$ per kg) between regime B and regime A when salmon were grown to respective harvest days.

Table 4.1. Table showing the number of meals per day in relation to season, water temperature, fish size and location. *S. salar* and *O. tshawytscha* were introduced as normal spring smolts.

Table 4.2. Weights, feed conversion ratio (FCR) and mortality of yellow tail fed by two different feeding methods and diets, where W_i =Initial weight, W_f =Final weight & M =mortality.

iv. List of Figures

Figure 1.1. Showing the AQ1 system including a conical pellet sampler, IR sensor, AQ1 controller and data pathway to the PC. Further sensor detail is shown in Fig. 1.2

Figure 1.2. The sensor and conical pellet trap in more detail

Figure 1.3. Flow chart displaying the feeding algorithm process pathway that controls the feeding output.

Figure 1.4. Example of the feeding algorithm used to control feed input based on the number of pellets detected. Note the relationship between excess feed and a subsequent reduction in the feed input. Note an increase in feed rate due to pellet detection rates being below the sensitivity threshold (sense high/low band).

Figure 1.5. The mean number of pellets detected by the underwater absolute pellet collection device and the IR sensor. The least wastage is apparent from treatment 1. The means are averages of number of meals (refer to table 1.1) with error bars depicting the upper standard deviation.

Figure 1.6. Graphs showing quarter hourly mean swimming speed (bodylength/second[a]), total feed intake (kg[b]), surface response (c) and light irradiation (quanta/second/cm[d]) on 20.5.92.

Figure 1.7. Grouped quarter hourly feed intake of 27 days during winter expressed as a percentage of the maximum quarterly value.

Figure 1.8. Diurnal quarter hourly feeding distribution expressed as a percentage of the total daily feed intake for consecutive days from the top graph 26.6.92 to the bottom graph 6.7.92

Figure 1.9. Graph showing the individual total daily feed intake (kg) from 20.5.92 until 7.7.92

Figure 1.10. Feed delivered (each bar is in seconds of feed distributed per actuation) over time (top graph) and the corresponding number of pellet detected per feed actuation (bottom graph). Data is shown for 2 night periods and one daytime period. Note very high pellet counts at each test output (0.5s of feed delivered) during the night and lower counts during the day, suggesting little or no significant feeding occurred at nighttime.

Figure 1.11. The mean number of pellets detected during the night and during the day that corresponded to 0.5s feed delivery. Note the consistently greater number of pellets counted during the night.

Figure 2.1. Relative diurnal feed intake of sea caged reared Atlantic salmon from 12.7.95 – 15.6.96 (as a % of the total daily feed intake per 15 minute interval). Data shown are for one of the replicate cages. Each horizontal grid represents 9 days of data.

Figure 2.2. Average monthly feed rate (%Body weight per hour \pm s.e., n=3) per month divided into the first hour of the day (filled circles) and the remainder of the day (open circles).

Figure 2.3a&b. (a) Average monthly water temperature expressed as ($^{\circ}$ C). Error bars are standard errors of the mean from daily readings at 0,2&4m depth. (b) Average monthly ration expressed as %Bodyweight consumed per day \pm s.e., n=3.

Figure 4.1. Schematic showing a typical configuration of the Adaptive feeding system in a sea cage.

Figure 4.2. The relative feed intake of Atlantic salmon (500-6400gms) in Tasmania, Australia, expressed as a percentage of total grouped (10 day intervals) daily intake. Note: uncorrected for daylight saving.

Figure 4.3. Average monthly weight versus year for smolt intake (1991-1994), from Huon Aquaculture Co, Tasmania, Australia.

Figure 4.4a. The relative feed intake of Chinook salmon (160-360gms) in spring, expressed as a percentage of the total daily feed intake. From Marlborough Sounds, New Zealand.

Figure 4.4b. The relative feed intake of Chinook salmon (1500-2200gms) in autumn, expressed as a percentage of the total daily feed intake. From Stewart Is., New Zealand.

Figure 4.4c. The relative feed intake of Chinook salmon (2200-2600gms) in winter, expressed as a percentage of the total daily feed intake. From Stewart Is., New Zealand.

Figure 4.5. The relative feed intake of Barramundi (1000-3000gms) in the dry season, expressed as a percentage of the total daily feed intake. From Darwin, Northern Territory, Australia.

Figure 4.6. PS1 pellet rate monitoring device.

Figure 4.7. Relative feed intake (% total daily feed intake) of *S. quinquerediata* during summer. Time of day (x axis) is in 15 min intervals. The number of days is shown on the y axis.

Figure 4.8a&b. a; top graph; showing the daily feed intake of yellow tail during summer. b; bottom graph; shows the cumulative feed intake over the same period. Note: the daily variation in feed intake.

v. List of Publications

Blyth P.J., Purser G.J. and Russell J.F. (1993) Detection of feeding rhythms in sea-caged Atlantic salmon using new feeder technology. In: *Fish Farming Technology*. (ed. by Reinersten H., Dahle L. A., Jørgensen L. and Tvinnereim K. Balkema). pp.209-215. A.A.Balkema, Rotterdam.

Blyth P.J., Kadri S., Valdimarrson S., Mitchell D and Purser G.J (1999) Diurnal and seasonal variation in feeding patterns of Atlantic salmon in sea cages. *Aquaculture Research* 30, 539-544.

Blyth, P. J., Purser, G. J. and Foster, C. K., (1992). Can compensatory growth improve the profitability of Atlantic salmon aquaculture? In: *Aquaculture Nutrition Workshop* (ed. G. L. Allan and W. Dall), Salamander Bay, 15-17 April 1991. NSW Fisheries, Brackish Water Fish Culture Research Station, Salamander Bay, Australia, pp. 227-231.

Blyth P.J., Purser G. J. and Russell J.F. (1997) Progress in fish production technology and strategies with emphasis on feeding. *Suisanzoshoku* 45 (1), 151-161.

Kadri. S., Blyth P.J. and Russell J. (1998) Feed optimization in finfish culture using an integrated “feedback” system with special reference to yellow tail, *Seriola quinqueradiata*. *Suisanzoshoku* 46, 423-426

This thesis comprises a number of publications as listed above. Some assistance in experimental design, field work, analysis and manuscript writing was received from co-authors and field technicians.

vi. General Introduction

All animals including fish have preferential feeding patterns and natural rhythms of behaviour that relate to changing biological and environmental factors (Eriksson and Alanara, 1992; Kavaliers, 1986; Thorpe and Cho, 1995). Daily feeding patterns and other activity rhythms of fish have been shown to vary seasonally, with age and species. These activities are suspected to be controlled primarily by exogenous factors of which photoperiod, temperature and feeding activity are considered the main determinants (see review by Boujard and Leatherland, 1992). Diel food intake patterns have been demonstrated for salmonids. Demand fed rainbow trout (*Oncorhynchus mykiss*) were shown to typically feed at dawn and dusk with some nocturnal activity during autumn and winter (Landless, 1976), a similar pattern noted for Arctic charr (*Salvelinus alpinus*) (Jorgensen and Jobling, 1989). Atlantic salmon parr (*Salmo salar*) in rivers also display a crepuscular pattern except in winter when more nocturnal activity occurs, associated with a reduction in crepuscular peaks of prey abundance. (Eriksson and Lundqvist, 1982; Fraser et al., 1993). More recent studies of Atlantic salmon parr grown in freshwater lochs in cages found feeding activity concentrated into the middle of the day when water temperatures increased (Noble in press). The few studies on adult Atlantic salmon in sea cages found they exhibit a diurnal crepuscular feeding rhythm (Blyth et al., 1993, 1999; Kadri et al., 1991; Thorpe et al., 1991). Feeding rhythms are a product of evolution and have evolved to maximize prey abundance, minimize predator avoidance and reduce inter-specific competition and thus stress (Thorpe and Cho, 1995). These rhythms should be used to improve aquaculture productivity.

Matching feeding regimes to the desired pattern of feed intake of cultured finfish species should be one aim of a husbandry plan. Feeding practice on commercial salmon farms is usually targeted at high growth while maintaining an acceptable feed conversion ratio (range 1.0 -1.3). Feeding fish to satiation can result in high growth but can lead to over-feeding or wasted food and thus lower conversion efficiency, aspects of which are reviewed by Brett (1979). The difficulty in commercial production is to apply an appropriate feed rate at a time when fish appetite is at its peak and continue this day after day without under- or over-feeding. Some studies have used automatic and demand feeders or hand feeding methods to present the feed ration (Alanara, 1992a&b; Boujard and Leatherland 1992b; Begout Anras 1998; Juell, 1991; Kadri, 1991; Landless, 1976) but none have used automatic feeders in combination with feed monitoring sensors to control feed intake such as in this study. Talbot (1996) described feeding rates of Atlantic salmon by using a "Lift-up™" system (air lift pellet and faecal collection apparatus) in combination with an Aquasmart Pty. Ltd. PS1 feed monitoring unit (an electronic device to monitor the rate of uneaten feed). More recently, post-1997, underwater cameras from numerous suppliers, acoustic pellet detection systems (Akva AS Doppler™) and infra-red pellet measuring devices (Storvik AS, recirculating pellet detection and capture device) have been used to detect satiation points during feeding in commercial farming situations. As yet there is no reviewed published data on the performance of these systems. Summerfelt et al. (1995) designed an acoustic sensor in combination with a simple "feedback" algorithm to regulate feed intake of fish in tank systems. Some work has been carried out on the use of video and image analysis to detect waste pellets in sea cages (Foster et. al., 1995) but as yet no commercial system has been developed. Other image analysis video research has focused on fish size and swimming speed

analysis and body size estimation (Beddow et al., 1996; Petrell et al., 1997; Storbeck and Daan, 1991) but as yet no commercial system has been derived these studies.

This study commenced in 1990 when it was identified that there existed no system to accurately measure and control feed intake of salmon in sea cages and there was no published material on the feeding patterns of Atlantic salmon in sea cages. Initially this study focused on the development of a system to control and record the feeding of Atlantic salmon in sea cages. This development occurred over a 4 year period after considerable field testing and refinement of prototypes. Hardware and software development was carried out in collaboration with Aquasmart Pty. Ltd. The developed equipment was capable of detecting waste feed in sea cages via an infra-red sensor together with a feeding algorithm (Adaptive™). Feeding was then controlled by automatically delivering an appropriate instantaneous feed rate that matched the feeding rate of the fish through feedback from the sensor. The system is now an industry standard and is widely accepted in the commercial and research global finfish aquaculture sectors.

Once the operational aspects of the equipment were standardized a series of trials were established to investigate feed distribution and optimal feeding strategies for Atlantic salmon. The experiments investigated Atlantic salmon diel and seasonal feeding rhythms in Tasmania and Scotland and the effect of restricted feeding times on compensatory growth of Atlantic salmon in Tasmania. A further extension of the equipment development included several commercial trials investigating the feeding patterns of yellow tail kingfish (*Seriola quinqueradiata*), Chinook salmon (*Oncorhynchus tshawytscha*) and barramundi (*Lates calcarifer*). The system has also been used to determine preferred feeding regimes of green back flounder, *Rhombosolea tapirina* (Chen et. al., 1999), Atlantic salmon parr in freshwater lochs (Noble et. al., 1999), Arctic charr, *Salvelinus alpinus*, in cages in Swedish freshwater lakes (University of Umea, unpub. data) and more recently Atlantic salmon parr feeding regime studies in tanks (research in progress, University of Glasgow).

A major impetus for the research came from the commercial salmon industry in Tasmania which deemed feeding regime research to be an area of major importance due to the potential for large production improvements. Also the feeding patterns of most commercially farmed species with the exception now of Atlantic salmon are not reported widely in the literature. The development and application of new feeding technology and new approaches to efficiently feed fish was therefore the focus of this thesis.

In summary the aim of the study was to

1. Develop equipment to measure and record feed intake of fish in sea cages (Chapter 1).
2. Determine diel feeding patterns, optimal feeding regimes and some key parameters implicated in the control of feeding of Atlantic salmon in sea cages (Chapter 2&3).
3. Determine applicability of the developed feeding system to other species of finfish farmed in sea cages (Chapter 4).

1. The “Adaptive” feeding system: preliminary studies

1.1 Description of the “Adaptive” feeding system

1.1.1 Introduction

Advances in automatic feeding systems for sea caged salmonids have seen the development of acoustic (Juell, 1991) and physically activated type of demand feeders (Landless, 1976; Boujard, et al., 1992; Brännäs & Alanärä, 1993; Sanchez-Vazquez et al., 1997), with only the demand systems proving to be viable in certain commercial situations. An assessment of a new type of automatic feeder (optical waste pellet detection feeder) was undertaken in this study, with the aim of gathering information about feeding patterns of caged salmon.

Various types of monitoring devices such as hydro-acoustic pellet detection units (Bentech AS described by Juell, 1993), hydro-acoustic biomass estimation/fish density and location systems (Simrad AS, Lindem Systems AS, Furuno Corp.) and infra-red scanning sensors to detect pellets (Aquasmart Pty. Ltd., described by Blyth et al., 1993) - see Figure 1.1, have been developed. A more recent attempt is in the use of doppler to measure pellets (Akva AS). Some have shown potential as feed management tools, while others have failed to benefit production.

Blyth et al., (1993), used behavioural observations of salmon in sea cages to develop a feed control and monitoring system based on detection of uneaten pellets, and use of this data (via an algorithm) to match feed input very closely to fish appetite. The Aquasmart “Adaptive™ “ Feeding System thus responded directly to instantaneous feed rate of the fish and so delivered feed in response to changes in feeding activity brought about by any number of behavioural, environmental, physiological and life history variables. This system was developed for the salmon culture industry where it has produced what are arguably the best production results worldwide. As this system created a cumulative database, it also provided information on feeding patterns of the fish populations, which are of interest to both fish biologists and feed managers alike. The system has been used successfully on other species and produced production improvements and a wealth of novel information in all cases (see Blyth et al., 1993, 1997). In Japan, where the system was trialed on yellow-tail for nearly two years, the feed rate aspects of the algorithm were altered in order to increase delivery rate and allow the system to match the feeding behaviour of this species. Some of the results from these trials are discussed in the chapter 4.

The aim of the device was to overcome the inefficiencies of some commercial equipment used for the feeding of fish in the Aquaculture Industry. In particular the difficulty of applying feed to the fish in a way that matched their preferential feeding patterns. Wild species introduced to aquaculture, and by degrees, semi-wild to domesticated species, exhibit broad feeding cycles that reflect their evolutionary niche diversification. Imposed on these broad feeding cycles are exogenous and endogenous factors that impose minor aberrations to the broad pattern. The device can be used to identify and adapt to macro- and micro- changes in feeding behaviour. The process ensures that fish are fed to satiation or if programmed to degrees of satiation ie; from sub-maintenance to satiation ration, while eliminating waste feed. The process aims to

grow fish at maximum growth (or below if required) while maintaining an efficient feed conversion ratio (FCR).

The system achieved this by detecting a sample or absolute amount of fish feed (by an underwater sensor) which passes through a school of fish occupying a particular net pen and uses the information to automatically regulate subsequent feed output (by an algorithm).

The underwater sensor was submerged to a depth dependent on the type of cage structure, average water conditions, the species feeding behaviour, number of fish in the cage, the age of the fish and the type of feed used. Fish feeding depth will also alter under certain environmental and temporal conditions. A feed dispenser is operated for a short time, typically 0.5 to 20 seconds, approximately every one to sixty seconds, although this will vary depending upon the peak feed consumption rate (maximum instantaneous feed intake), the minimum instantaneous feed intake and the feed distribution hardware

This chapter discusses the operation of a system used to automatically control and record feed intake. The system was then calibrated in a sea cage. The final sections cover some preliminary studies using the system to identify the diurnal feeding patterns of Atlantic salmon in sea cages in Tasmania.

1.1.2 System components

The feeding system consists of a control unit (CU), a conical pellet trap (CPT) with an optical sensor attached, all linked to a feed dispenser and the control unit (Figure 1.1). The control unit is a programmable computer with the capacity to run multiple feeding programs and store data (64kb memory). The CPT consists of a plastic fabric cone having a diameter of 1.5m and height of 1m attached to a pellet sensor. This amounted to an available capturing area of 1.8m². The CPT for optimal results was positioned directly beneath a feed hopper. A sample of uneaten pellets were detected shortly after activation of the feeder by the CU.

Sensor

The sensor is an infra-red (IR) based technology, comprising a IR source and sink positioned approximately 60mm apart (Figure 1.2). The source beam is directed to a parabolic mirror from where it is reflected back across an aperture to an opposing parabolic mirror where it is directed back to the IR sink. The loss of light when an object passes through the resulting sheet of IR light is measured and processed electronically. This signal is then analyzed by the central micro-processor, by wave-form analysis. Statistics are then used to group classes of particles.

Sensing technique and object discrimination

The sensor uses automatic gain to establish a standard light level through the aperture, prior to sensing objects. This feature allows and detects for partial aperture blockage and turbidity variation and can be used to determine whether a sensor is blocked or partially blocked.

The sensor is calibrated to establish an appropriate range that maximizes definition of a set of objects that have passed through the aperture. Wave-form measurements on individual objects are recorded and a group mean and standard deviation are stored. Out-liers are rejected. Individual object wave-form measurements can also be stored. Definition and discrimination of the calibrated object as opposed to any other foreign material is carried out by comparison of the wave-form values of an un-calibrated object compared to calibrated values.

The detection accuracy of the feeder is to single pellet precision. Gain adjustment made it possible for the sensor to recognize pellets as small as 1/8 inch (3mm diameter). Before the feeder can operate a calibration procedure must be followed to allow the feeder to specifically recognize pellets as opposed to algae, faeces, invertebrates or any other foreign matter that may pass by the sensor. Recognition of pellets is critical to the successful operation of the unit.

Feed distributor

Various feed distribution devices have been used in conjunction with the "Adaptive" feeding system in the study and will be discussed in the relevant section as they pertain to the actual experiment.

Feeding algorithm

The "Adaptive" feeding algorithm, utilizes an underwater sensor to discriminate pellets and then "decide" on an appropriate feeding level. The following section covers the parameters that are used to establish ranges within which the algorithm can function. Figures 1.3&1.4 shows the process in a flow chart format. System parameters (sensor calibration and program settings) are initially set by the user and after a period of operation (approximately 1 week) enough data is collected by the system for the system to automatically evaluate the best or most appropriate feeding rate and frequency and /or sensor calibration values, and to test if the user defined settings were appropriate. The system stores the feed input, pellets counted and events such as setting changes or events such as hardware condition.

Feeding Algorithm Definitions

Sink rate: The sink rate (cm/s) of the pellet being used in combination with the sensor depth is used to determine the time taken for pellets to reach the sensor.

Depth: This is the depth (metres) from the water surface to the sensor.

Gain: This adjustment is from 1-5. Five is the highest gain, allowing total definition of pellets while 1 significantly eliminates background "noise" if present. With larger

feed sizes it is more common to use a gain of 3-5 while very small feed may require a gain of 1-3.

Sense-time: Sense-time is the time in seconds that the sensor operated after a feed delivery.

The AQ1 bases all operations on daily feeding programs with settings defined by the user. Each program divides the day into time intervals or steps. These intervals are specified by means of a Start Time eg. 08:00, and a Stop Time , eg. 10:30.

Start Time: The step start time.

Stop Time: The step stop time.

Mode: There are two settings available, either slow or burst. For normal feeding operation slow increased feed output in a linear fashion, while burst feed doubled output.

Pause: The Pause time is the minimum time between each feeder actuation during feeding.

Sleep: The sleep period is the period that the system does not operate in between feeding periods or meals.

Minimum sleep: The minimum sleep time is the smallest time that the feeder will remain inactive after a feeding bout or meal has been completed.

Maximum sleep: The maximum sleep time is the longest period that all operations are suspended after a feeding bout. Over the day, within a step, the *Sleep* period will automatically change between the minimum and maximum sleep settings to home in on the preferred temporal feeding pattern of the fish.

Minimum feed: This is the minimum amount of food delivered.

Maximum feed: This is maximum amount of food delivered by the feed distributor. The upper limit can be constrained by the size of the cage, feeder spatial distribution pattern and maximum number pellets ingested per fish per minute. The appropriate instantaneous intake rate is determined by auto ranging between the minimum and maximum feed values.

Sensitivity: The sensitivity is an arbitrary level of feed detected and can be set to an individual value ie; a band of acceptance can be created sense low = 1 sense high = 5. The value represents a single feed pellet of the type calibrated. The sense low/high values control the threshold of algorithm action, sleeping or feeding.

High Repeat: This value sets an upper threshold of times that the algorithm will operate consecutively at maximum spin. The value set will depend upon the time of day, biomass, and water current velocity.

Data collection

All feeding data was stored in control unit memory. This information was retrieved by a portable data logger, radio or hard-wired methods, passed onto an IBM-compatible PC for analysis and interpretation utilizing customized feeding software.

1.1.3 Calibration of the system in a commercial sea cage

An attempt was made to examine the effect of different system settings on absolute feed waste. The aim was to determine whether the “usual” system parameters utilised on the commercial farm were adequate in minimizing waste. The sensor depth and sense threshold values were judged to have the most impact upon absolute pellet wastage and were therefore evaluated in more detail.

Materials and Methods

A single 60m circumference circular type cage was used in the experiment. A pellet collection device was placed under the net on the cage to retrieve all wasted feed particles. The system consisted of a large plastic conical shaped tarpaulin with an air hose spliced into a 75mm diam. pipe going to a surface sieve box. Material was lifted by an air lift created by the air upwelling through the pipe.

The cage was stocked with 3792 Atlantic salmon (mean weight 2.82kg) at a stocking density of 7.5kgm³. The trial was conducted during 2.7.95-10.7.95. The fish were fed to satiation at each meal, three times per day. The first meal commenced at 0900, the second at 1300 and the third at 1600. The fish were delivered feed by the AQ1 system with the meal finishing when the system detected waste sufficient to automatically stop according to the program settings used (Table 1.1). During the meal at 15 minute intervals any excess feed particles were pumped up to the surface and recorded. Gibsons Ltd. steamed pressed 6mm diameter pellets were used.

Each treatment was carried out in triplicate over time for the trial period. Treatments were assigned randomly to the meal period in an attempt to normalize for time of day.

Table 1.1. Showing the treatment and system parameters

Treatment	System settings	Number of meals
1	Sensor depth = 4m, sense low-high threshold (1-5 pellets)	N=5
2	Sensor depth = 4m, sense low-high threshold (5-15 pellets)	N=2
3	Sensor depth = 6m, sense low-high threshold (1-5 pellets)	N=6
4	Sensor depth = 6m, sense low-high threshold (5-15 pellets)	N=6

Results

Treatment 1 showed the least waste compared to the other treatments (Fig 1.5). Further work could address a wider range of parameters eg. different fish size, fish stocking densities and pellet sizes in order to establish a more complete understanding of the relationship between system settings and total waste. This was outside the scope of this thesis.

Chapter 1.2 has been removed for
copyright or proprietary reasons.

It has been published as: Blyth, P. J., Purser, G. J., Russell J. F., 1993. Detection of feeding rhythms in sea-caged Atlantic salmon using new feeder technology. In: Fish Farming Technology. (ed. by Reinersten, H., Dahle, L. A., Jorgensen, L. Tvinnereim K. Balkema). pp.209-215. A.A.Balkema, Rotterdam.

1.3 Do adult Atlantic salmon feed at night in sea cages?

1.3.1 Introduction

The purpose of this section was to determine whether salmon of 5kg fed during the night. Research has shown that salmon parr can feed at night under very low light conditions during winter (Fraser et al. 1993). This experiment was designed to test whether adult salmon in Tasmania under full moon conditions fed when water visibility was good.

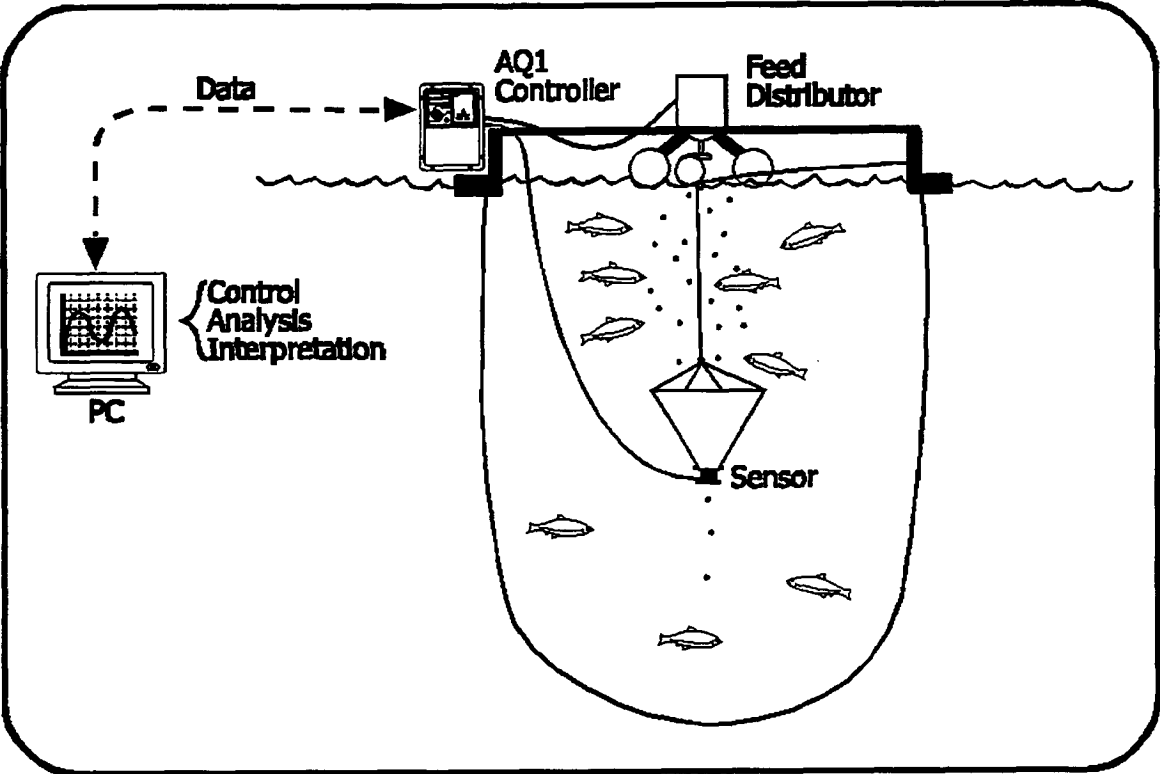
1.3.2 Methods and Materials

A single cage of Atlantic salmon were fed with an adaptive feeder which was programmed to operate through the night, using settings from the previous day. One test output occurred every 15minutes. The experiment was carried out from 18/11/94-22/11/94. The moon was full on 18/11/94 and the evening was cloudless.

1.3.3 Results and Discussion

The data shows that salmon did not feed or consumed such small quantities as to be insignificant during the night over the course of the experiment as highlighted in figure 1.10. The average number of pellets counted by the sensor during a test delivery was compared between the day and at night to establish whether the value increased at night. Figure 1.11 shows that the number of pellets counted at night was always greater suggesting that over the 5 day experiment little or no feeding occurred at night. A switch from nocturnal to diurnal behaviour may occur between parr and salmon based on this brief study and that of Fraser et al. 1993. The implications to the fish farmer are that they do not need to consider night feeding as a strategy for adult salmon.

Figure 1.1. Showing the AQ1 system including a conical pellet sampler, IR sensor, AQ1 controller and data pathway to the PC. Further sensor detail is shown in Fig. 1.2



Sensor and conical pellet sampler

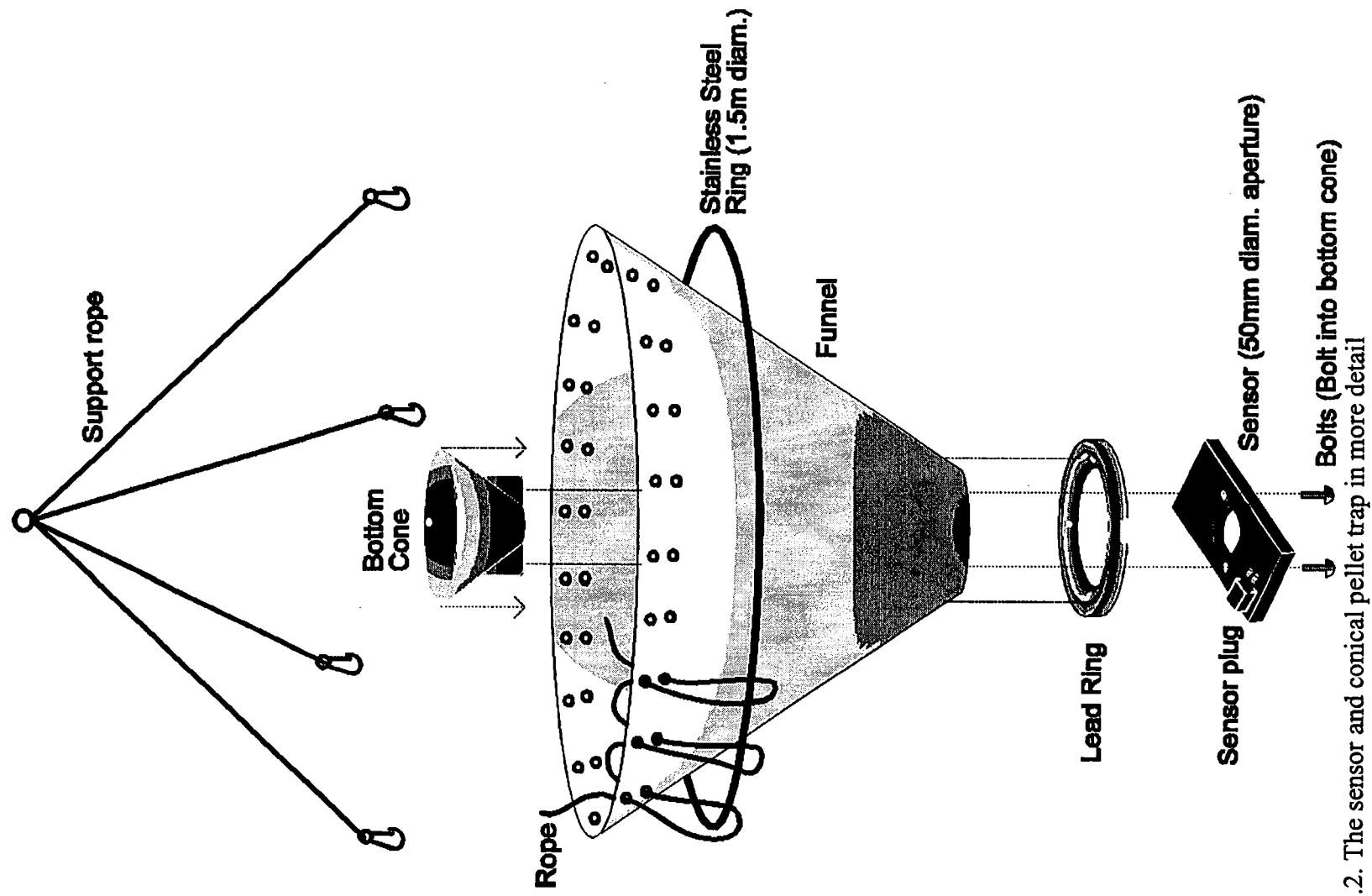


Figure 1.2. The sensor and conical pellet trap in more detail

A Feed Cycle

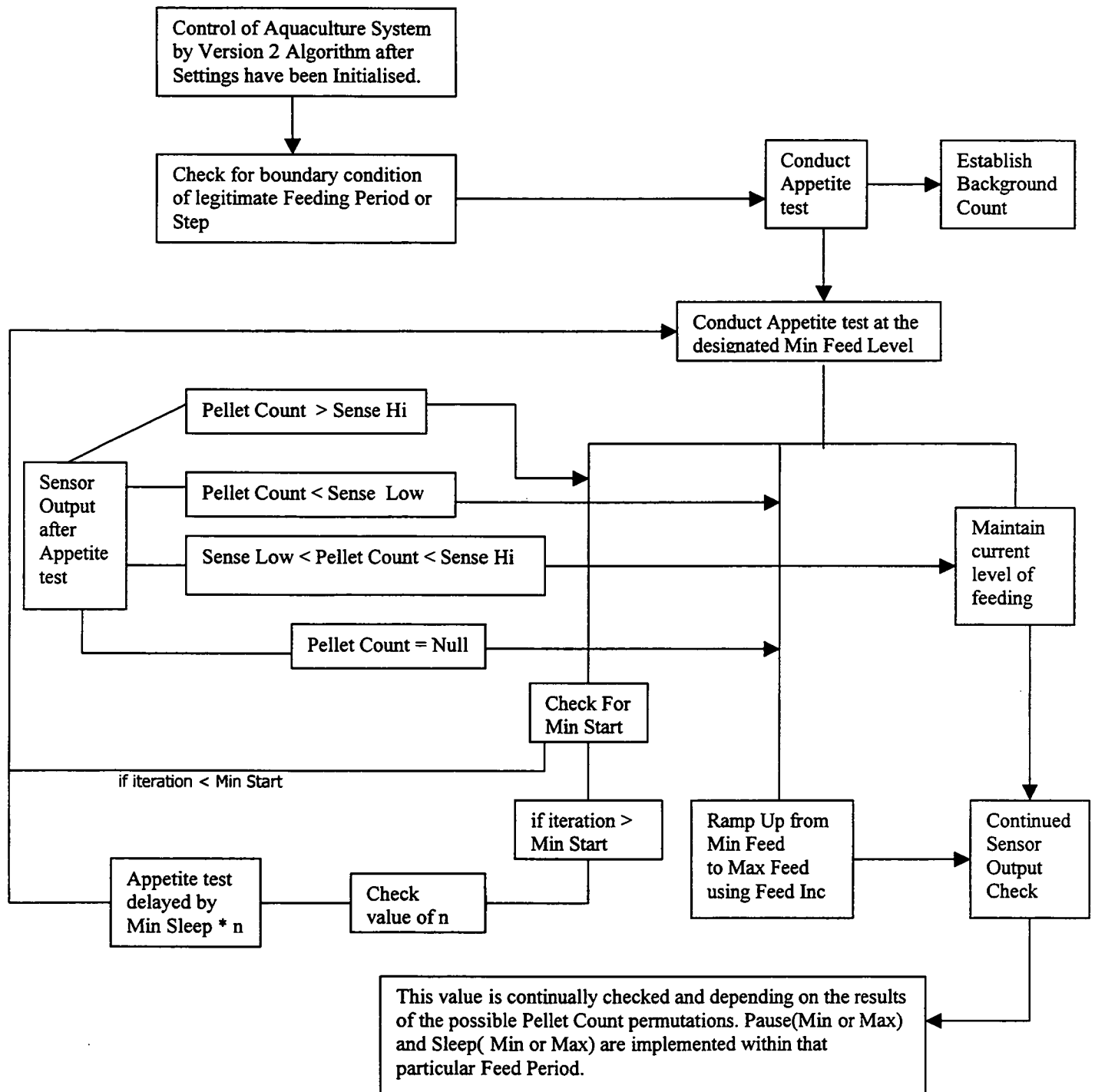


Figure 1.3. Flow chart displaying the feeding algorithm process pathway that controls the feeding output.

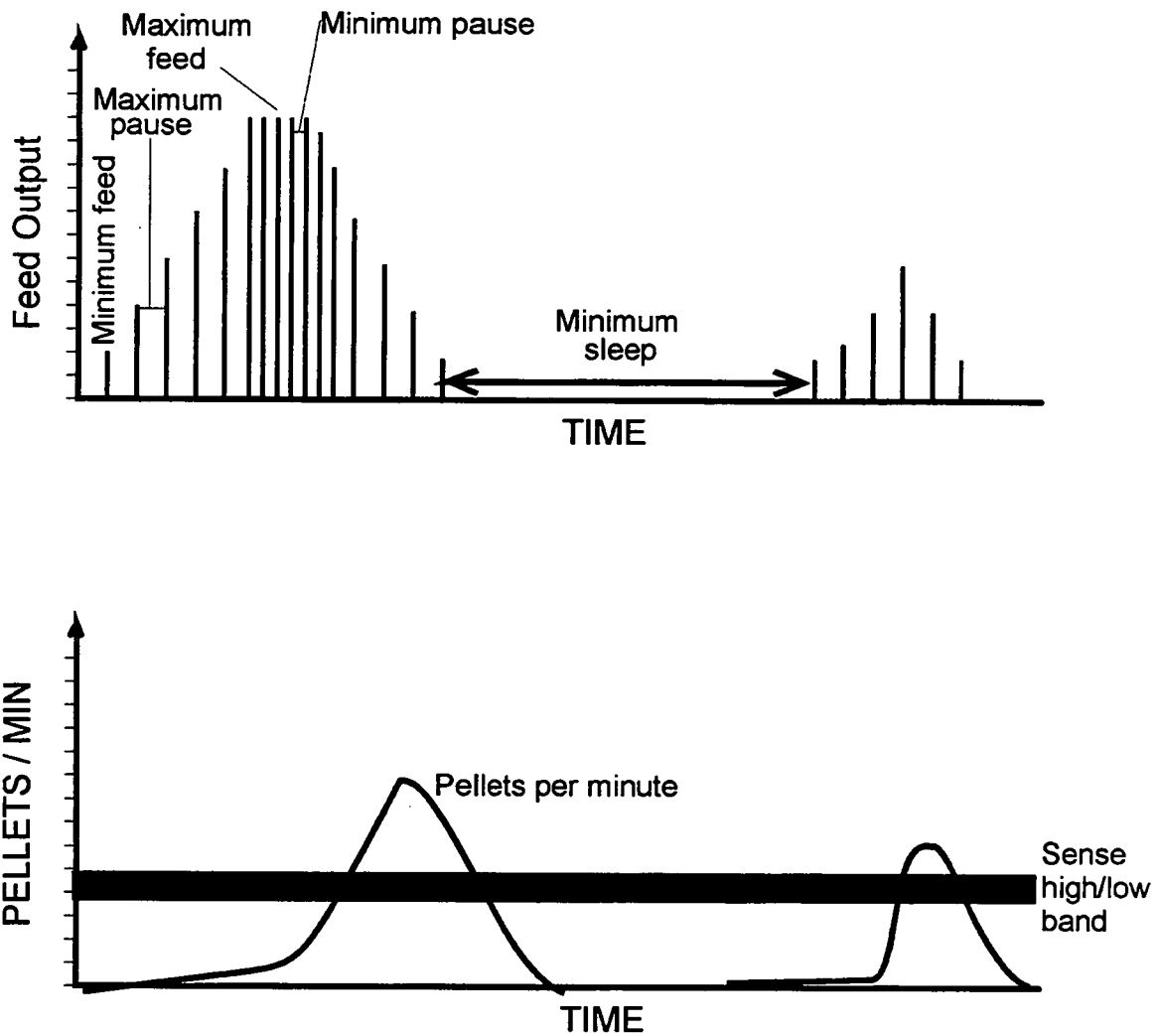


Figure 1.4. Example of the feeding algorithm used to control feed input based on the number of pellets detected. Note the relationship between excess feed and a subsequent reduction in the feed input. Note an increase in feed rate due to pellet detection rates being below the sensitivity threshold (sense high/low band).

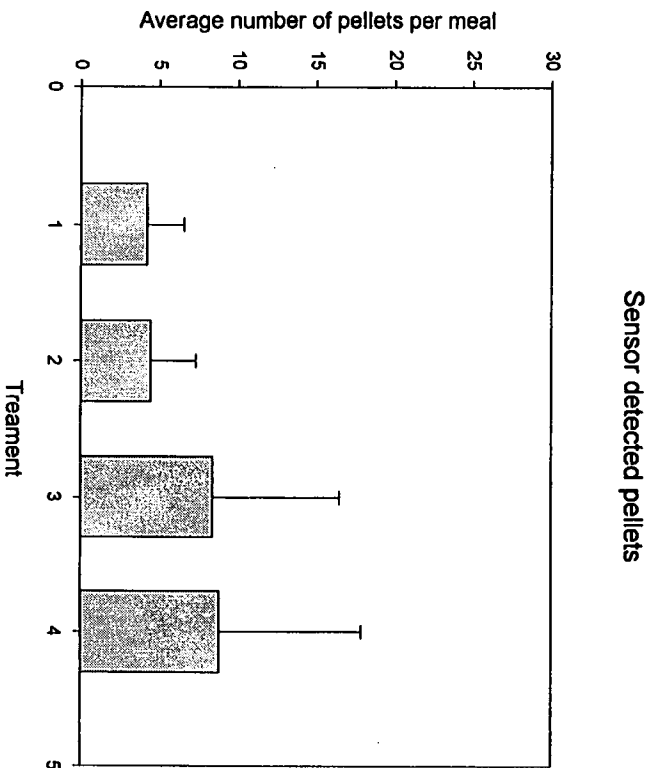
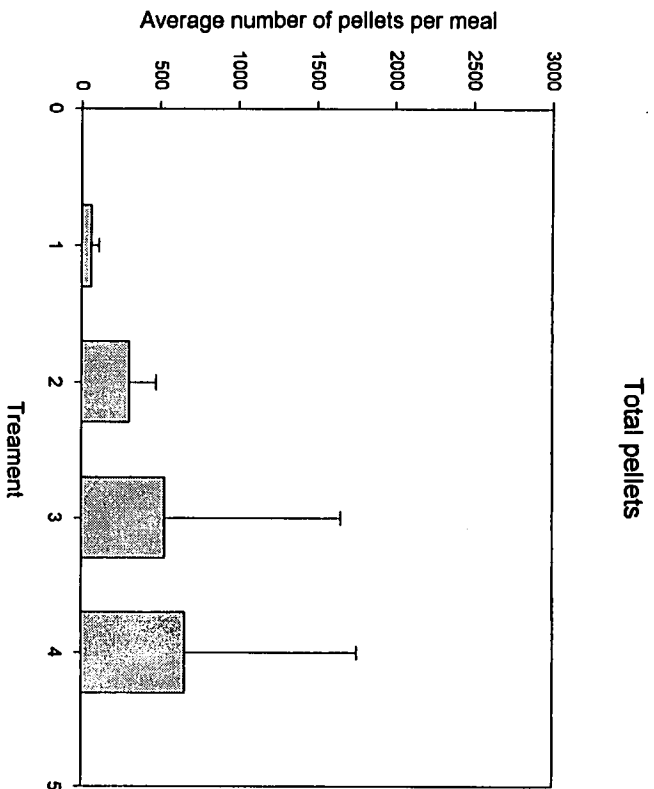


Figure 1.5. The mean number of pellets detected by the underwater absolute pellet collection device and the IR sensor. The least wastage is apparent from treatment 1. The means are averages of number of meals (refer to table 1.1) with error bars depicting the upper standard deviation.

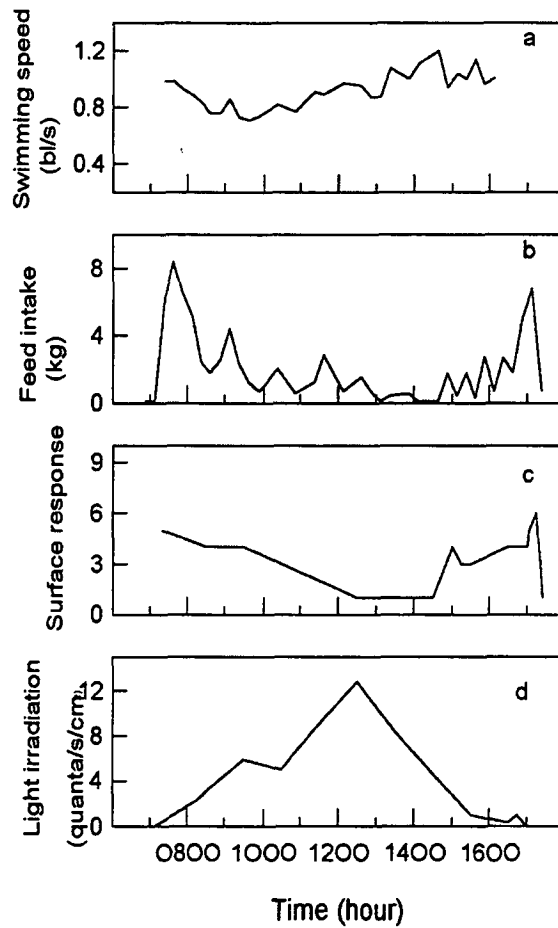


Figure 1.6 Graphs showing quarter hourly mean swimming speed (bodylengths/second [a]), total feed intake (kg [b]), surface response (c) and light irradiation (quanta/second/cm[d]) on 20.5.92.

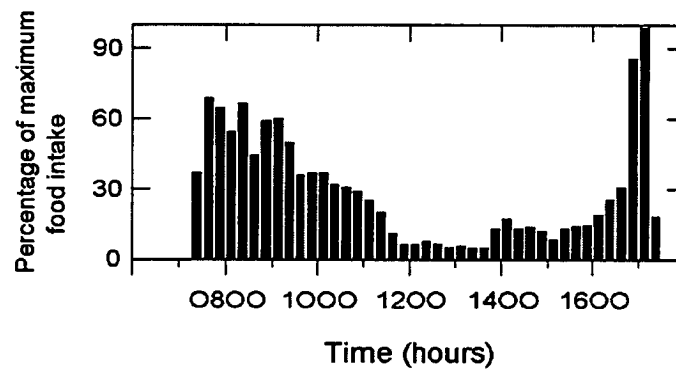


Figure 1.7 Grouped quarter hourly feed intake of 27 days during winter expressed as a percentage of the maximum quarterly value.

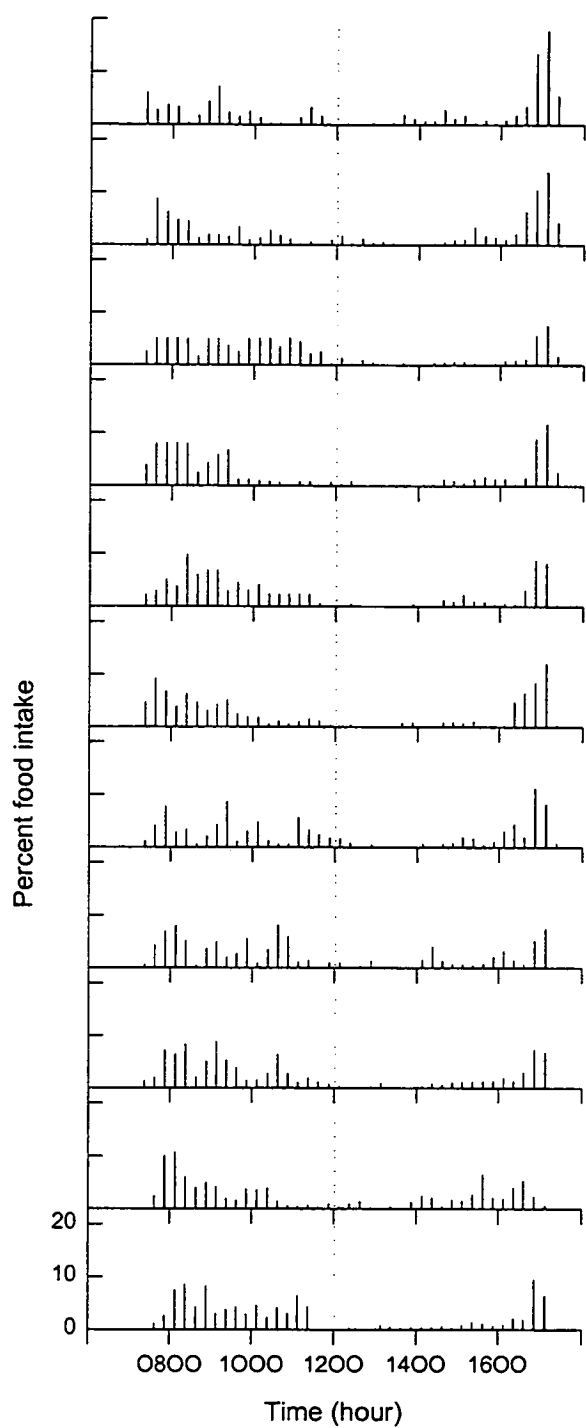


Figure 1.8 Diurnal quarter hourly feeding distribution expressed as a percentage of the total daily feed intake for consecutive days from the top graph 26.6.92 to the bottom graph 6.7.92.

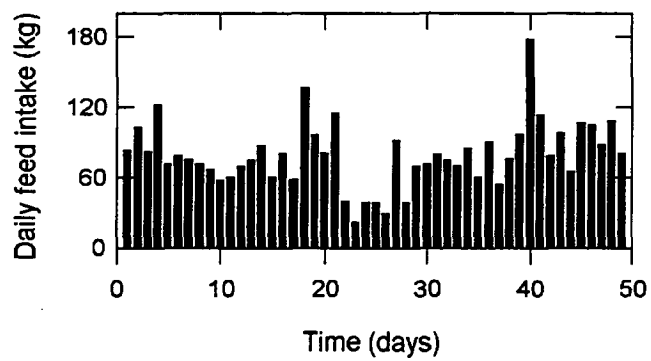


Figure 1.9 Graph showing the individual total daily feed intake (kg) from 20.5.92 until 7.7.92.

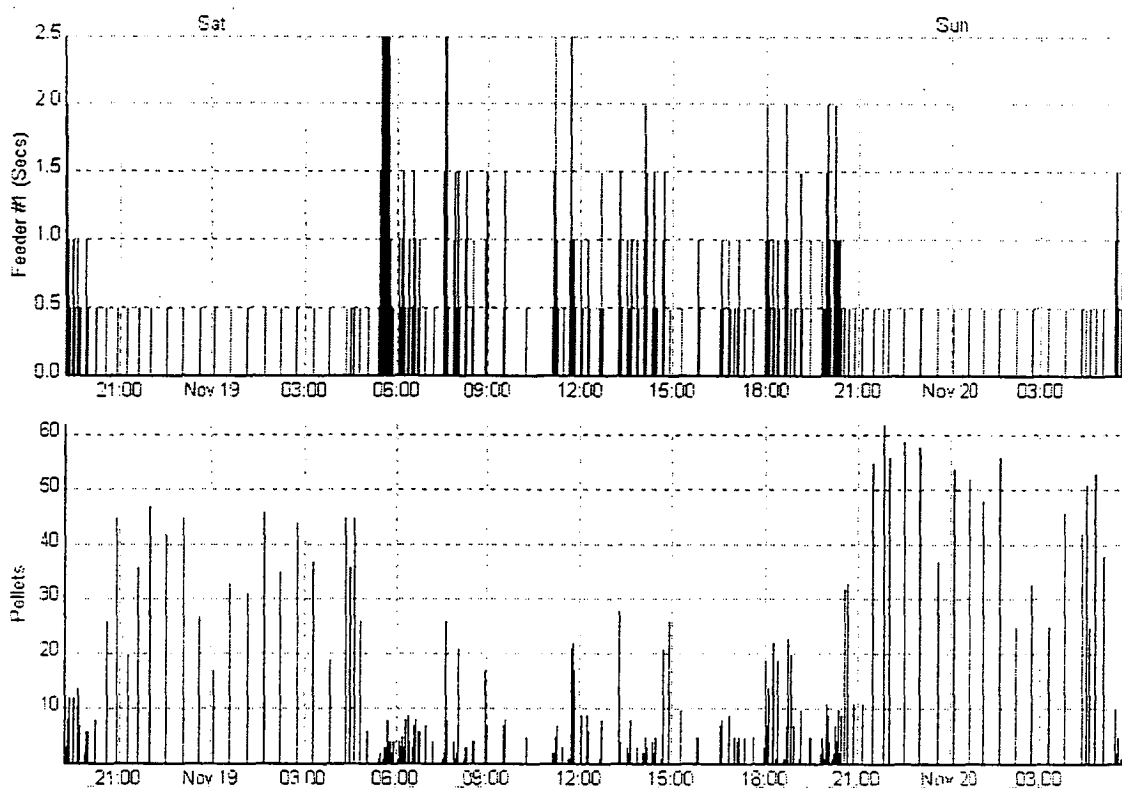


Figure 1.10 Feed delivered (each bar is in seconds of feed distributed per actuation) over time (top graph) and the corresponding number of pellet detected per feed actuation (bottom graph). Data is shown for 2 night periods and one daytime period. Note very high pellet counts at each test output (0.5s of feed delivered) during the night and lower counts during the day, suggesting little or no significant feeding occurred at night.

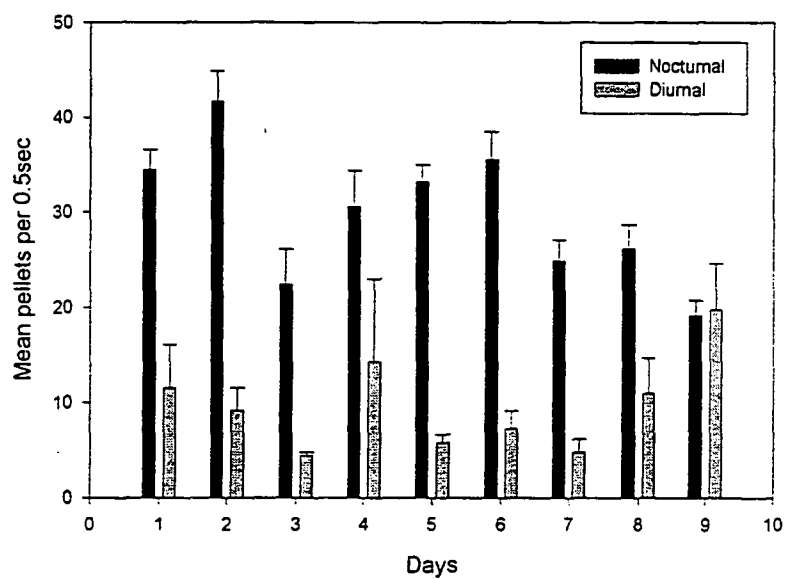


Figure 1.11 The mean number of waste pellets detected during the night and during the day that corresponded to 0.5s feed delivery. Note the consistently greater number of pellets counted during the night.

2. Diurnal and seasonal variation in feeding patterns of Atlantic salmon in sea cages

Blyth P.J, Kadri S., Valdimarrson S., Mitchell D and Purser G.J (1999) Diurnal and seasonal variation in feeding patterns of Atlantic salmon in sea cages. *Aquaculture Research* 30, 539-544

2.1 Introduction

Long term studies aimed at identifying of feeding patterns of adult Atlantic salmon *Salmo salar* L. in sea cages are few. Diel feeding patterns of salmonids have been examined but usually over short time periods (Landless, 1976; Jørgensen & Jobling, 1989; Thorpe et al., 1991; Kadri et al., 1991; Smith et al., 1993; Alanärä, 1993; Blyth et al., 1993). Most of these studies were constrained by an inability to collect data continuously. Two types of feeding devices are currently available that enable feed demand to be monitored. These are: self-feeders operated by a trigger mechanism (Landless, 1976; Boujard et al., 1992; Brännäs & Alanärä, 1993; Sanchez-Vazquez et al., 1997) and interactive feeding systems of the type described by Blyth et al., (1993).

Fish can be generally classified into three groups that reflect the period during which feeding occurs, nocturnal, diurnal and crepuscular although other factors such as tide can influence feeding time (Johannes 1981). Sea bass, *Dicentrarchus labrax* L., have been shown to exhibit circadian feeding rhythms that can change between nocturnal and diurnal (Sanchez-Vazquez et al., 1997). Bégout Anras, (1995) found that sea bass had a feeding peak after dawn and a preference to feed at lower light levels. The feeding pattern of rainbow trout *Oncorhynchus mykiss* (Walbaum) also seems to be crepuscular with a dawn peak (Landless, 1976; Boujard & Leatherland, 1992a; Brännäs & Alanärä, 1993). Arctic charr, *Salvelinus alpinus* (L) appear to change their feeding pattern according to season (Jørgensen & Jobling 1989). Atlantic salmon are generally regarded to be crepuscular feeders with a primary feeding peak occurring just after dawn (Higgins & Talbot, 1985; Thorpe et al., 1991; Kadri et al., 1991; Blyth et al., 1993) As an exception, parr have been reported to feed nocturnally during winter (Fraser et al., 1993; Valdimarsson et al., 1997).

The aim of this study was to examine the feeding patterns and rates of Atlantic salmon held in sea cages throughout the marine production cycle.

2.2 Materials and Methods

The trial was carried out at a Marine Harvest McConnel FTU (Feed Trial Unit) site in Loch Duich, Scotland, (57° 15' N 5° 30'W) using three sea cages (5x5x5m) each of which was stocked with 500 Atlantic salmon, from the Lochy stock. At the start of the trial on 10.7.95 the average weight of the fish was 159g. The trial terminated on 21.6.96 when fish were harvested with a mean weight \pm SE of 4073 \pm 53g.

The three cages were automatically provisioned with feed by AQ1 feeding systems (Aquasmart Pty.Ltd. Australia), which incorporated an infra-red (IR) pellet sensor linked to a microprocessor and embedded feeding algorithm (for further description see Blyth *et al.*, 1993). The AQ1 system controlled a 12VDC dosing motor in

combination with a circular spreader (Sterner AS, Sweden). The IR pellet sensing device was positioned 3m beneath the water surface sampled an area of 1.8m².

Daily feeding commenced 30-90min. after sunrise and the AQ1 feeding system continued to offer feed every 30 min until twilight. The feeding algorithm was programmed to deliver feed every 30 min during the day. When uneaten pellets were registered by the sensor then the system “slept” for 30 min. If no pellets were counted the algorithm commenced increasing the feed input at pre-set rate until a point was reached where pellet detection occurred, then, the rate of delivery was slowed. It was assumed fish were fed daily to satiation. Feed input from the distribution device (kg/s) and pellets passing the sensor (pellets/s) were recorded in a database. Extruded feed from BP/Trouw Nutrition was used in the study and is described in table 2.1.

Water temperature (°C) was recorded daily at the water surface, 2m and 4m from 6.10.95 to 30.6.96.

To test for variation in feed provisioning between months the average rate of feed supply was calculated in terms of %Body-weight per hour. This was then further divided into the first hour of the day and the average of the remainder of the day. Repeated measures ANOVA was used to test for differences between the first hour of the day and for differences between the months. In a further seasonal comparison the average %Body-weight per day was calculated for each month and repeated measures ANOVA was used to test for differences.

At each sample point (Table 2.3), 100 fish were randomly taken from each replicate cage, anaesthetized with benzocaine then weighed. Specific growth rate was calculated using combined cage data, as there were no significant difference between the cages, at each weight sample ($SGR = (\ln(\text{final wt}) - \ln(\text{initial wt}) / \text{number of days}) \times 100$). Gross monthly feed input was also recorded to allow calculation of feed conversion ratio ($FCR = \text{kg feed delivered} / \text{kg change in biomass}$).

2.3 Results

The salmon usually showed a peak in feeding early in the morning and then subsequently lowered their feed rate, this pattern was evident throughout the year (Fig. 2.1&2.2). Each month feed intake was significantly greater in the early morning than later in the day (Table 2.2; Fig. 2.2). The difference between the early morning rate and that later in the day was greatest during the first summer, when the fish were 150-1000g (Fig. 2.2). At the end of the trial the difference in feeding rates between early morning and later was small.

The average monthly feed rate changed significantly over time (Table 2.2; Fig. 2.2 & 2.3b). A rapid decrease in daily feeding rate occurred in September around the time of the autumn equinox. After this decline the feeding rate remained lower than it was in July-September. Water temperature peaked in November at 12.3°C and declined to a low of 6.6°C in February (Fig 2.3a).

Fish grew from 150g to an average of 4.3kg during the trial. The period FCR generally increased with time (Table 2.3) whereas SGR declined. A greater than

expected mean cumulative FCR (1.4) was recorded and may be attributed to the excess feed input testing sequence (appetite test every 30min) employed in the trial.

2.4 Discussion

The diurnal pattern of feeding activity amongst the Atlantic salmon was characterised by a significant morning peak throughout most of the production cycle. A similar pattern has been described by others, although some variation is apparent. A crepuscular feeding pattern has been observed for 1kg salmon in summer but no clear feeding peaks were seen in autumn, winter or spring for salmon 2-3kg (Kadri et al., 1991; Smith et al., 1993). These studies were conducted using automatic feeders that delivered feed continuously over the day (according to feed manufacturers' tables) and feeding responses were monitored at intervals during the day. Blyth et al., (1993) and Blyth et al., (1997) examined feeding patterns of Atlantic salmon in Tasmania and found a similar crepuscular pattern to Kadri et al., (1991). Differences between studies may have arisen due to variation in feed quality, cage size, stocking density or environmental conditions (eg: temperature and day-length).

As feed was available only during daylight hours it could be argued that feeding rhythms may have been influenced by a restricted feeding regime, as suggested by Boujard & Leatherland (1992b), rather than being synchronized to the light/dark cycle. There is however evidence that salmon held in sea cages do not feed at night (Smith et al., 1993). In autumn and winter a secondary feeding peak, or an extension of the morning feeding peak, occurred (Fig.1), but this could not be revealed from the analysis of grouped data (Fig.2). The extension of the morning feeding peak observed during autumn and winter may have been related to the fact that fish had gone several hours without feeding during the night (Fig 1). Autumn and winter feeding patterns may also have been associated with a higher feed intake by fish that would mature in their second sea summer compared to immature individuals. The physiological status of the fish in respect to accumulated energy reserves is linked to maturity (Kadri et al., 1996), although maturing salmon become anorexic prior to the start of the spawning season (Kadri et al., 1997) as reflected by the June feed rate data (Fig. 1&2).

There are benefits for the aquaculturist to feed fish according to their preferred feeding pattern: These may include improvements in production performance resulting from increased growth and better feed conversion (Boujard and Leatherland, 1992b) and reduced stress due to predator avoidance requirement. Feeding patterns may also provide clues to the fishs' well being and supply the farmer with information about when the stock deviate from a "normal" feeding pattern. If the pattern is abnormal, causes can be sought and remedied. From an aquaculture management perspective the present results need to be placed in the context of extrapolation to larger commercial sea cages, which would involve study of the effects of cage size and stocking density upon temporal and spatial variation in feeding.

Table 2.1. Diet type and the content of oil and protein as a percentage of the total composition of the feed used throughout the annual cycle.

Feed type	Period	Oil : Protein (%)
BP/Trouw 40	4.5.95-7.9.95	27:47
BP/Trouw 50	7.9.95-5.10.95	30:46
BP/Trouw 60	5.10.95-21.12.95	30:46
BP/Trouw 85	21.12.95-16.5.96	33:41

Table 2.2. Results of a repeated measures ANOVA showing the effect of time of year (month) and part of day (1st hour of the day against the remainder of the day) on the average feed intake (% Body-weight per hour) of sea-caged reared Atlantic salmon.

Source	<i>Df</i>	<i>MS</i>	<i>F</i>	<i>P</i>
Month	11	0.007055	12.12	<0.001
Error (month)	22	0.000582		
Day part (1 st h or rest)	1	0.114070	1767.82	<0.001
Error (Day part)	2	0.000065		
Interaction	11	0.003518	11.19	<0.001
Error (Interaction)	22	0.000314		

Table 2.3. Mean weight gain (g) and feed conversion ratio (FCR) of Atlantic salmon reared in sea cages throughout an annual cycle. FCR data are represented as mean \pm S.E. (n=3). Mean weight gain from one replicate cage is represented.

Sample period	FCR	Mean weight gain (g)
10.7.95 - 10.8.95	1.24 \pm .15	127
10.8.95 - 20.9.95	0.91 \pm .10	337
20.9.95 - 2.10.95	0.99 \pm .05	408
2.10.95 - 14.12.95	1.17 \pm .02	678
14.12.95 - 15.2.96	1.13 \pm .08	330
15.2.96 - 28.3.96	2.25 \pm .09	1,256
28.3.96 - 16.5.96	1.25 \pm .06	177

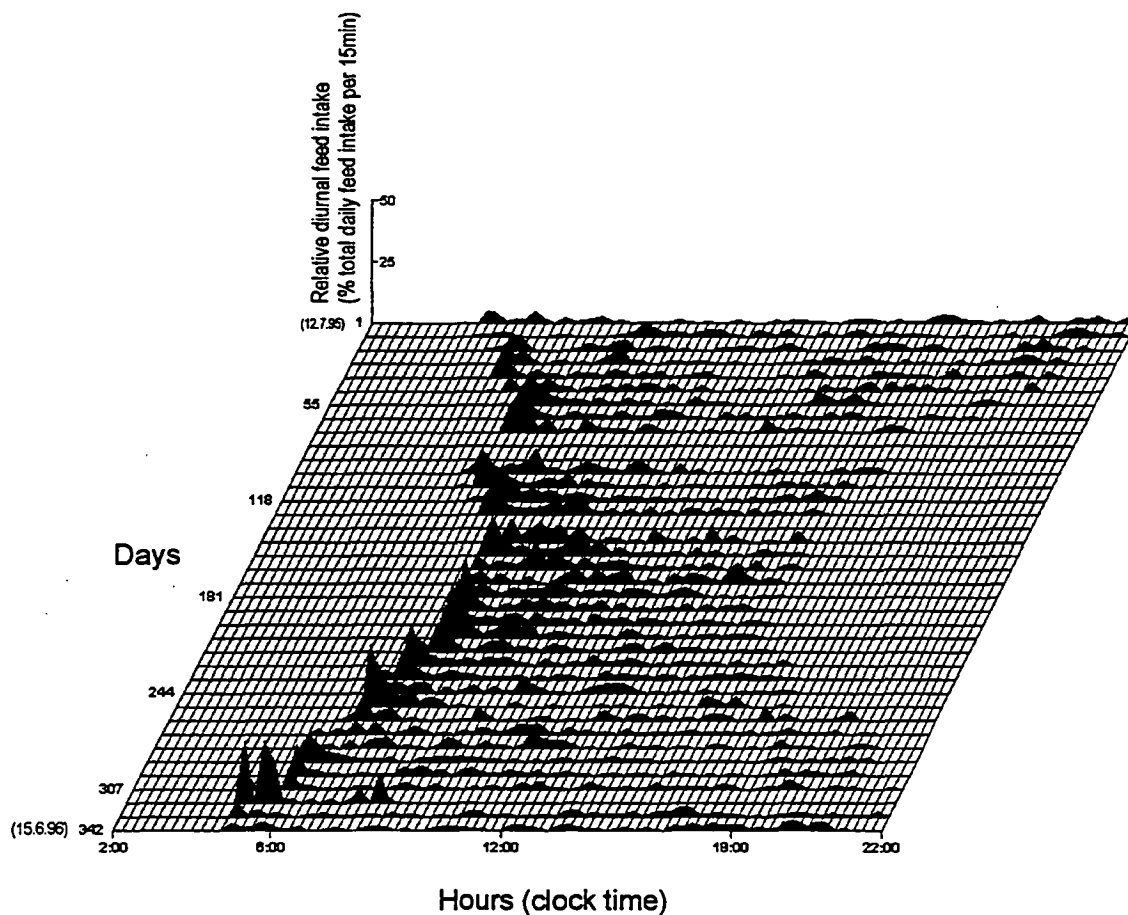


Figure 2.1. Relative diurnal feed intake of sea caged reared Atlantic salmon from 12.7.95 – 15.6.96 (as a % of the total daily feed intake per 15 minute interval). Data shown are for one of the replicate cages. Each horizontal grid represents 9 days of data.

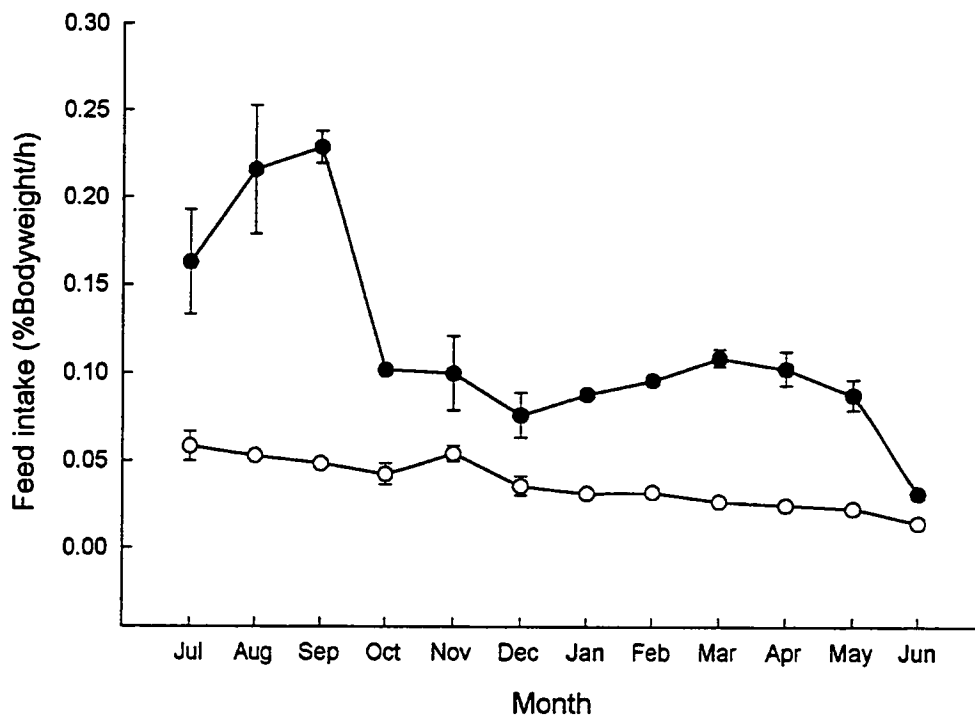


Figure 2.2. Average monthly feed rate (%Body weight per hour \pm s.e., $n=3$) per month divided into the first hour of the day (filled circles) and the remainder of the day (open circles).

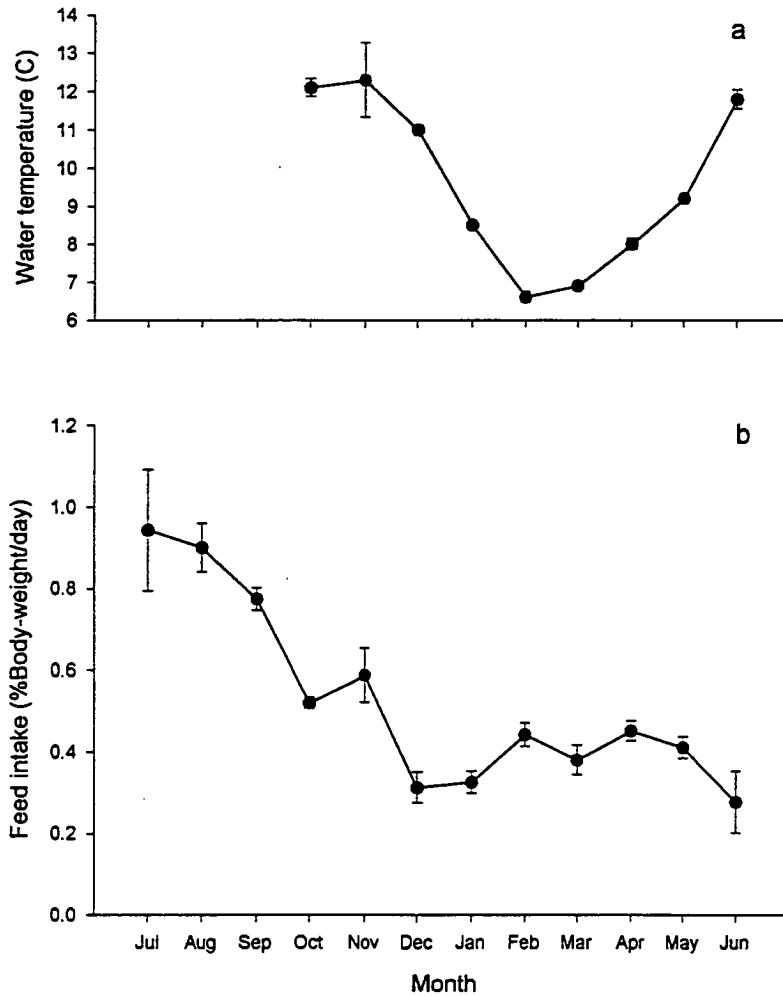


Figure 2.3a and b. (a) Average monthly water temperature expressed as (°C). Error bars are standard errors of the mean from daily readings at 0,2&4m depth. (b) Average monthly ration expressed as %Bodyweight consumed per day \pm s.e., n=3.

Chapter 3 has been removed
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reasons.

It has been published as: Blyth, P. J., Purser, G. J., Foster, C. K., (1992). Can compensatory growth improve the profitability of Atlantic salmon aquaculture? In: Aquaculture Nutrition Workshop (ed. G. L. Allan and W. Dall), Salamander Bay, 15-17 April 1991. NSW Fisheries, Brackish Water Fish Culture Research Station, Salamander Bay, Australia, pp. 227-231.

Chapter 4.1 has been removed
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It has been published as: Blyth, P. J.,
Purser, G. J., Russell J. F., 1997. Progress
in fish production technology
and strategies: with emphasis on feeding,
Suisanzoshoku 45(1), 151-161.

Chapter 4.2 has been removed
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It has been published as: Kadri. S., Blyth,
P. J., Russell J. F., 1998. Feed
optimisation in finfish culture using an
integrated "feedback" system with
special reference to yellow tail,
Suisanzoshoku 46(3), 423-426

vii. General Discussion

This study has contributed to the development of equipment used to control feeding of Atlantic salmon in sea cages and identified key aspects that govern good production performance of fish in aquaculture such as feeding rhythms and appropriate feeding rates of this species, from a temporal (diel and seasonal) and geographic (Tasmania and Scotland) perspective.

Feed control equipment

Feed monitoring and control technology during the last 6 years has become more common place in the global sea cage aquaculture industry. Early feed collection devices such as the Lift-up™ system are being replaced by devices such as developed in this study as well as more recent acoustic systems (Akva Doppler™). Other devices such as (Storvik AS) which uses feed re-circulated through an infra-red sensor are also out in the market. There are also several systems in the development phase investigating video (Poro A/B) and standard acoustic analysis (Biosonics Ltd and Guigne Ltd.). All sensor systems have limitations which include turbidity affecting video, currents affecting all methods, differences in maintenance requirements and sample size constraints. The Adaptive™ feedback algorithm is a key component of the system developed in this study and contributes to feeding efficiency significantly as determined from commercial studies conducted around the world comparing this technology to all the other methods mentioned. Presently the Aquasmart Pty.Ltd. Adaptive™ feeding system commands the largest market share with over 1500 systems worldwide.

Feeding patterns

Fish display patterns of activity that are driven by evolutionary adaptations to their natural environment (Forrester et al. 1994, Thorpe and Cho, 1995). Salmonids in the marine stage of their life cycle are typical diurnal feeders (Blaxter, 1980) and periodically exhibit nocturnal behaviour as parr (Fraser et al., 1993; Higgins and Talbot, 1985).

Variation in daily feed intake in salmonids has been shown to occur due to environmental change (Brett, 1979) or due to the natural growth and feed intake rhythms (Boujard and Leatherland, 1992a; Eriksson and Alanara, 1990; Farbridge and Leatherland, 1987; Kadri et al., 1991; Smith et al., 1993).

From this series of studies it has been shown that salmon of all ages take the largest meal of the day in the early morning, on average 15 minutes after dawn. Up to a size of 700gm the fish can take multiple small meals during the day after which the meal frequency decreases to 2-3 meals up until harvest weight of 3-6kg. The daily feed intake is further influenced by the size, season/daylength and sexual status of the fish. These patterns are influenced by extreme conditions such disturbance from predators or the physical environment, for example, when the water temperatures are at the lower end of a species optimum range then the number of meals will decrease to one per day, alternate days or other variations. This was observed in this study for *S. salar*, *O. tshawytscha* and *S. quinquerediata*. Others studies confirm these observations (Kadri et al., 1991, 1996a, Smith et al., 1993)

Feeding rate and satiation time

The main factors effecting the satiation time and amount are size of fish, temperature, length of deprivation period prior to feeding, digestibility of the diet and nutrient quality of the diet (Brett, 1971; Crayton and Beamish, 1971; Elliot, 1975a, b; Grove et al., 1978). Salmonids are generally regarded as requiring more time than most other teleosts to reach satiety, even when more than enough food is presented (Vahl, 1979). Most work indicates that commercial sea cages stocked with Atlantic salmon greater than 1kg take about 2 hours to reach satiation in the morning feed, and reduced times for later feeds in the day, assuming the initial morning feed was to satiation (Juell, 1988; Storebakken and Austreng, 1988a). The main meal in this series of studies varied in duration from 30-120 minutes. These times are similar to the satiation times noted in this study although Talbot (1997) reported shorter durations (13minutes.) Salmon feed rates reported in this study were usually < 0.2kg/tonne of fish/minute compared to higher values in the Talbot (1997) study (0.2-0.5 kg/tonne of fish/minute). The ability of fish in this study to access feed for a longer period during the day, every day, due to automatic delivery of the feed, was suspected to result in the lower feeding rates compared to other studies and from some commercial operations. The method used in this study was not detrimental to the growth or feed conversion efficiency of the fish (pers. obs.).

Restricted feeding

Restricting feed intake by feeding below an expected daily satiation ration or temporally by missing meals or complete days of feeding are strategies designed to control harvest planning and reduce operational costs due to labour (Forsberg, 1999). Restricting feed access in terms of time can result in lost growth over a long term as seen from this study and others (Alanara, 1992; Jobling, 1983; Johansen and Jobling, 1998). In this study weight difference between treatments became significant after 2 months on restricted feeding regimes, factors that would negate its commercial adoption as a high growth strategy. Compensatory growth in fish has been observed by others using various feeding regimes different to this study (Juell, 1988; Miglavs and Jobling, 1989; Quinton and Blake, 1990) who all showed fish re-introduced to satiation feeding after restriction show improved feed conversion efficiency but not growth. Further to this Johansen and Jobling (1998) found daily restriction of ration will result in lost growth. They also observed that fish fed to satiation displayed the poorest feed conversion efficiency. This has also been observed from several studies with the Aquasmart Adaptive feeding system and raises several issue about the growth/ration curve and exactly where the optimal feed conversion point lies. The best use of restricted feeding regimes still requires further research to design effective strategies to suite the animals' age and conditions under which it is farmed.

Production performance

Improvements in production performance over the last 5 years in the salmon industry have been dramatic with many farms now recording an FCR of 0.9-1.1 for fish of harvest weight 3-4kg, particularly farms using AQ1 equipment. Fish growth has not experienced the same gains as FCR, as the focus has been on feed efficiency and cost rather than size increase. This is best seen from Norway and UK particularly with *S. salar* and to a lesser extent other markets. Huon Aquaculture Co. in Tasmania has

recorded best FCR's in the range 1.1-1.3. Differences in feed conversion efficiency between the various global salmon grow-out areas can be attributed to environmental conditions, feed quality, genetic stock and feed management and technology.

Management implications

Current farm practice is to feed fish daily to satiation in discrete meals and to satiation within a meal. This has shown to result in the highest growth although care must be taken to not over-feed and create poor FCR at this point. Indications are that rainbow trout *O. mykiss*, are proving an exception to this rule in that they are subject to hyperphagia, also noted by Jobling (1983). The focus of fish farmers is usually to grow fish as quickly as possible while maintaining the best feed conversion ratio, unless market forces dictate otherwise. The need to use monitoring equipment to measure the satiation point and help determine the correct input rate is important. This study has clearly identified preferred feeding times of salmon in Tasmania and UK and provided a technique which optimises growth and feed conversion efficiency.

Summary

Some of the key points to come out of the study are:

1. The development of apparatus (Aquasmart Pty. Ltd., AQ1 Adaptive feeder™) to measure, automatically regulate and record feed intake of fish in sea cages.
2. Identification of diurnal and seasonal feeding patterns of Atlantic salmon in Scotland and Tasmania. Atlantic salmon were found to feed primarily in the morning and evening with smaller fish eating several other meals during the day. This pattern was similar to that reported by Kadri (1996a) and was repeated in both hemispheres except during the short Scottish winter days when one morning meal only was observed.
3. Identification of appropriate feed rates for Atlantic salmon. Feed rates were compared with those reported by Talbot (1994) and Talbot and Korsoen (1997). and were found to be slightly lower. Longer feeding periods were suspected to be the major cause for the lower values recorded in this experiment as Talbot and Korsoen (1997) fed fish in two or one meal per day which is suspected to have raised rates due to reduced feeding time opportunity.
4. Application of this technology to commercial fish farms has assisted in development of cost-effective feeding regimes demonstrated by improved feed conversion ratios and growth rates. Results from 40 Norwegian fish farms using AQ Adaptive™ technology in 1999 confirm on average 10-20% improvement in FCR for fish harvested over the range 3-7kg.
5. Swimming speed varied in accordance to time of day and feeding state. Ang and Petrell (1998) also found that Atlantic salmon exhibited strong circular swimming motion during non-feeding periods which soon devolved into a more disorganised pattern during feeding. They also found that twilight light levels caused a decrease in food detection, a factor noted in this study.
6. The effect of restricting feeding period on the compensatory growth response of Atlantic salmon was investigated and shown to occur, although several months on a restricted regime caused growth loss.
7. The technology has been successfully applied to yellow-tail kingfish, salmon and smolt in lochs, red sea bream, Chinook salmon and barramundi.

Future developments

Feeding strategies are still an area requiring further study. Most commercial feed management strategies for salmon feed fish daily to satiation, in meals, particularly during their rapid growth periods. Variation to this practice will occur due to physiological state of the fish eg: maturation, or extreme environmental conditions such as cold water causing a reduction in feeding response. The use of restricted feeding regimes for a certain period of time during the production phase has not been adopted by the industry, even though this study and others have shown potential benefits. Further research should concentrate on the best periods for the “compensatory” response to be employed.

This study has identified diurnal feeding rhythms in salmonids and other species. These rhythms appear to vary due to size and season (eg. temperature and light) with short term aberrations possibly caused by extreme weather and/or predators. This study has shown salmon prefer to consume feed during the early morning and late evening with the number of meals during the day varying primarily with fish size. A more detailed analysis of the effect of these factors on feeding is essential to complete the understanding of salmon feeding behaviour in sea cages.

Future technical development in feed management systems for fish in cages will see the integration of environmental monitoring systems, advanced sensing devices (such as video and acoustic systems) and feeding equipment more suited to exposed locations and larger culture systems. Effective feeding strategies should consider the behavioural constraints of the species. The culture unit, species and feeding system must be viewed as a part of a total system in order to achieve the best outcome for the farmer and the fish. The development of equipment to farm fish is still in its infancy although significant progress has been made. The next generation of systems will further enhance production efficiencies.

This study has allowed further insight into the behaviour of sea caged salmon. There is much work to be done to understanding circadian and circannual rhythms of sea-caged teleosts. It will then be up to the aquaculturist to use this information to provide the fish with a comfortable environment, so production benefits and the fishes welfare is enhanced. The ‘adaptive’ feeding system will make this work easier.

viii. References

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